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X-RAY DIFFRACTION INVESTIGATION OF MINOR PHASES

OF 20 HIGH-TEMPERATURE ALLOYS

By B. M. Rosenbaum

Flight Propulsion Research Laboratory
Cleveland, Ohio

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SUMMARY

X-ray diffraction methods were used to identify the minor phases present in 20 high-temperature alloys in current use: 16-25-6, 17W, 19-9DL, Discaloy 25, S590, N155, K-42-B, Refractaloy 26, Nimonic 80, Inconel W, Inconel X, Inconel, Vitallium, 61, Stellite No. 6, 6059, 422-19, X-40, S816, and Hastelloy B.

The seven minor phases found to exist in the various alloys were columbium carbide, columbium nitride, titanium carbide, titanium nitride, chromium carbide (Cr_7C_3), and carbides of the $M_{23}C_6$- and M_6C-types in which the ratios of metal M to carbon atoms are, respectively, 23:6 and 6:1. The following relations were found from the results of this investigation:

1. When the ratio of the atomic percentage of titanium to that of carbon is 12.5 in the nickel-base alloys, titanium nitride is found.

2. Columbium and titanium are effective nitride and carbide formers.

3. When titanium is not present in these alloys, in order for columbium alone to combine with all the carbon of an alloy, it must exist in a quantity appreciably above that theoretically required.

4. In the high-temperature alloys containing a quantity of chromium in the order of 20 percent with small percentages, relative to the carbon content, of other stronger carbide-forming elements, the carbide Cr_7C_3 is found.

5. With an increase in the ratio of the atomic percentage of molybdenum and tungsten to the atomic percentage of carbon available to these elements for combination, the carbide containing the molybdenum and tungsten atoms tends to change from $M_{23}C_6$ to M_6C.

INTRODUCTION

Carbides, nitrides, and other phases distributed throughout the matrix of alloys play a significant role in determining the characteristics of the alloys. An element dissolved in the matrix may alter such properties of the matrix as corrosion and oxidation resistances, hardenability, strength, and crystal structure. When a minor phase appears in an alloy, stresses within the matrix result and these stresses may exert a great influence on the high-temperature properties of the alloy such as creep and stress-rupture strengths. The identification of these minor phases in an alloy is important in determining the distribution of the elements of the alloy among the phases.

Knowledge of the manner in which a specific element is distributed among the various phases of an alloy would permit evaluation of the function of that element in the alloy. This information would also help in selecting the percentage of an element required in a new alloy containing the same types, but not the same quantities, of minor phases as alloys previously studied. For example, chromium in solution in an iron-base matrix is well known to produce excellent resistance to oxidation by forming a tightly adhering oxide film on the surface under oxidizing conditions. Chromium, however, is a carbide-former; if all the chromium in such an iron-base alloy forms carbides, this resistance to oxidation is lost. Therefore, if chromium is to be dissolved in the matrix of an iron-base alloy in a sufficient amount to give a specified oxidation resistance, the manner in which chromium distributes itself among the carbide phases and the matrix must be considered in determining the percentage of chromium that the alloy should possess.

Although a large amount of research has been conducted on the compositions of the minor phases of steels, light alloys, and copper-base alloys, little research has been published on the compositions of the minor phases present in high-temperature alloys in current use. The minor phases in Vitallium, a cobalt-base alloy, have been investigated microscopically by Badger and Sweeny, who found the phases $M_{23}C_6$ (where M is any metallic atom of the alloy), M_6C, and Cr_7C_3 to be present (reference 1).

An investigation was therefore conducted at the NACA Cleveland laboratory to identify the minor phases existing in 20 high-temperature alloys and to obtain a pattern of the relations between the composition of these alloys and the formation of their minor

phases. The 20 alloys are representative of the materials employed
in current gas-turbine applications. The identification of the
minor phase was based on a determination of their crystal structures
through the use of X-ray diffraction methods.

ALLOYS

Typical chemical compositions of the 20 alloys — 16-25-6, 17W,
19-9DL, Discaloy 25, S590, N155, K-42-B, Refractaloy 26, Nimonic 80,
Inconel W, Inconel X, Inconel, Vitallium, 61, Stellite No. 6, 6059,
422-19, X-40, S816, and Hastelloy B — are shown in table I. The
alloys are divided by composition into groups: Cr-Ni-Fe base,
Cr-Ni base, Cr-Co base, Cr-Ni-Co base, and Mo-Ni base.

All the alloys possess face-centered cubic crystal structures
at room temperature with little difference in lattice parameters.
Measurements showed that the lattice parameters of 12 of these
alloys (reference 2 and unpublished NACA data) range from 3.5525 to
3.5975 angstrom units.

The samples were taken from hot-rolled bars, except those
designated cast in table I; samples from these alloys were taken
from specimens in the as-cast state.

APPARATUS AND PROCEDURES

X-ray and electron diffraction and chemical and spectrographic
analyses were considered for use. Chemical and spectrographic
analyses were rejected because of the difficulty of obtaining pure
minor-phase samples necessary for these methods. Electron diffrac-
tion was also rejected because of its sensitivity to the thin
reaction films that may form on the surface of the specimen during
any processing treatments (reference 3). X-ray diffraction was
therefore used. The preparation of samples for X-ray diffraction
examination entailed the digestion of the alloys to increase the
concentration of the minor phases.

Concentration of minor phases. - The minor phases can be con-
centrated by electrolytically digesting the alloy in a bath of a
reagent that selectively dissolves the matrix; this process deposits
a residue of high minor-phase concentration on the bottom of the
bath. If several samples of an alloy are subjected to electrolytic
attack by different reagents, each reagent dissolves the alloy
phases in varying proportions. Because the phases present are

unknown, a number of reagents are employed in an attempt to con-
centrate each of the minor phases as a residue in at least one
reagent. By a comparison of the patterns of the several residues
so obtained, the interference lines due to each phase may be dis-
cerned and identification of the phase made accordingly.

The following electrolytic digestion agents were used, each at
concentrations of 50 and 150 grams per liter of aqueous solution
except for the oxalic acid reagents, in which concentrations of 50
and 100 grams per liter were employed:

1. Hydrochloric acid, HCl

2. Nitric acid, HNO_3

3. Sulphuric acid, H_2SO_4

4. Phosphoric acid, H_3PO_4

5. Chromic acid, H_2CrO_4

6. Oxalic acid, $H_2C_2O_4$

7. Acetic acid, $HC_2H_3O_2$

8. Aqua regia, $HNO_3 \cdot HCl$

9. Ferric chloride in hydrochloric acid, $FeCl_3 \cdot HCl$

10. Phosphoric-sulphuric acid, $H_3PO_4 \cdot H_2SO_4$

11. Sodium hydroxide, NaOH

12. Ammonium hydroxide, NH_4OH

Twenty-four samples of each alloy were cut and each served as the
anode in one of the twenty-four electrolytic baths; in each bath
a carbon rod was the cathode. A thimble surrounded the cathode to
avoid contamination of the residue by any deposit that might fall
from the cathode. A current of approximately 1.5 amperes was
passed through each bath for a period of 24 hours. At the com-
pletion of this digestion period, two specimens were collected from
each bath. One was the residue, which was filtered from the bath
and washed with distilled water, and the other was the coating that
was scraped from the anode. The anode coating served as a check on
the results obtained with the residue.

X-ray diffraction. - Debye-Scherrer powder cameras, 57.3,
114.6, and 143.2 millimeters in diameter were employed in obtaining
diffraction patterns of the specimens, which were ground to below
200-mesh size. The three camera diameters were used to save time.
Cr, Fe, Co, and Cu radiations were used with filters of V,
Mn, Fe, and Ni, respectively. Specimens for the largest camera
were mounted on cotton threads impregnated with mineral oil; speci-
mens for the other cameras were mounted on thin glass rods with a
mixture of 3 parts amyl acetate to 1 part Ambroid cement as the
binder. During exposure to the X-ray beam, specimens in the largest
camera were oscillated through 20°, whereas those in the other
cameras were rotated slowly. The relative intensities of the lines
on the developed film were estimated visually. The line spacings
were measured to the nearest 0.1 millimeter.

Final identification of the minor phases was based on the
patterns obtained with the camera of largest diameter. If lines
not previously identified were observed in the patterns obtained
with the smaller cameras, another diffraction pattern of that
specimen was taken with the 143.2-millimeter camera. Identifica-
tion of the minor phases was made by comparing the interplanar-
spacing data obtained with those of compounds of the alloying
elements listed in the literature and in the A.S.T.M. card index.

EXPERIMENTAL RESULTS AND LIMITATIONS

This investigation did not result in identification of all
residues obtained; the unidentified diffraction patterns are listed
in table II. The patterns of this table have been compared with
those of compounds of the alloying elements listed in the A.S.T.M.
card index and, in some cases, close agreement has been found. How-
ever, the compounds whose patterns agree with those listed in
table II have a large number of isomorphs and the composition of
each phase therefore cannot be established.

The residue yielding the first pattern in table II appears to
be a mixture of two phases: The first phase yields a pattern most
similar to that of rhombohedral iron oxide, Fe_2O_3; the second com-
pares most closely with the spinel type of compound such as face-
centered cubic cobalt chromite, $CoCr_2O_4$. Pattern 3 is similar to
that of rhombohedral α-iron oxide monohydrate, $\alpha\text{-}Fe_2O_3 \cdot H_2O$
whereas patterns 7 and 14, which are markedly similar, seem to
correspond to the pattern of β-iron oxide monohydrate,
$\beta\text{-}Fe_2O_3 \cdot H_2O$. Pattern 4 agrees closely with that of rhombohedral

iron titanate, $FeTiO_3$. Pattern 9 contains lines that indicate the presence in this residue of a face-centered cubic phase with a lattice parameter of 4.17 angstrom units, comparable with nickel oxide, NiO. The last pattern appears to be a combination of the pattern of β-iron oxide monohydrate (patterns 7 and 14), and the rhombohedral iron oxide (pattern 1).

Interplanar spacing values and intensities of the interference lines of the seven minor phases found in the alloys investigated are tabulated in table III. The symbol M used in this table represents any metallic atom of the alloy under consideration; that is, the formulas $M_{23}C_6$ and M_6C indicate carbide types in which the ratios of metal to carbon atoms are, respectively, 23:6 and 6:1. As will be shown later, this notation is used because of the uncertainty that exists about the composition of these particular minor phases. Table IV shows that the lattice parameters of the minor phases, titanium carbide and carbides of the $M_{23}C_6$ and M_6C types, were found to vary in different alloys outside the limits of experimental accuracy. The value of the lattice parameter of each phase identified in each alloy is listed in table IV.

A complete tabulation of the patterns of the residues obtained with each reagent for every alloy is given in table V.

The minor phases identified in each of the 20 high-temperature alloys examined are listed in table VI. The alloys are listed according to the principal metallic elements present and are arranged under these headings in accordance with their minor elements. The elements are listed in an order making for ease of comparison between alloy compositions. In the Cr-Ni-Fe-base alloys and in the Cr-Ni-Co-Fe-base alloys considered in this report, molybdenum is the most commonly used minor element. In the Cr-Ni-base alloys, titanium and aluminum or titanium and columbium are present although copper, in one instance, is used alone. In the Cr-Co and Cr-Ni-Co alloys, tungsten and molybdenum are used. The last group, represented by only one alloy, comprises Mo-Ni-base alloys.

The identification of these particular minor phases does not indicate the absence of any other minor phase but only the presence of those identified. Minor phases may have been present in some alloys in such small amounts that they were not concentrated in any of the residues to the minimum concentration required for detection by diffraction methods. Some minor phases present also may have been soluble, partially or completely, in all of the 24 electrolytes

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used; if so, their percentages in the residues may have been reduced, rather than concentrated, as compared to those in the alloy.

The possibility always exists that reaction products formed during the digestion process may have been insoluble in the reagent and collected with the residue. With oxalic acid, reaction products were thus collected and, consequently, the patterns of residues of the high-temperature alloys electrolytically digested in oxalic acid were identified as those of mixtures of the oxalates of cobalt, nickel, and iron.

Another factor to be considered in the identification of minor phases is that these phases should not necessarily be regarded as true compounds possessing the exact formulas shown. A substitutional solid solution of the other elements present in the compounds corresponding to these formulas may exist. For example, cementite, which is usually written as Fe_3C and which occurs in plain carbon steel, is a well-known example of the lack of distinction that exists between a solid solution and a compound. Small additions of carbide-forming alloying elements to carbon steel can be accommodated, to a limited extent, by replacement of the iron atoms of the cementite; cementite, therefore, can contain up to about 15 percent chromium (reference 4, p. 78), the chromium atoms occupying the positions of the iron atoms that they have displaced throughout the crystal lattice. When the percentage of the carbide-forming element is further increased, the cementite can accommodate no additional foreign atoms and a new carbide phase, richer in the alloying elements, forms. Although X-ray diffraction yields information on the crystal structure of the material examined, it does not directly give the elements that make up the compounds. Isomorphs of the compounds listed as identified may therefore have been present.

COMPARISON WITH MINOR PHASES OF FOUR TYPES OF STEEL

Inasmuch as five of the seven compounds identified in the high-temperature alloys have been previously observed in steels, a survey of the intermetallic compounds observed in steels containing the same alloying elements as the high-temperature alloys was made.

Table VII shows the carbides, nitrides, and intermetallic minor phases identified in low- and high-alloy steels (references 4 to 8). Of these compounds, those found also in the high-temperature alloys investigated are indicated and are

chromium carbide, Cr_7C_3; carbides of the $M_{23}C_6$ and M_6C types; titanium nitride, TiN; and titanium carbide, TiC.

In a series of chromium steels of increasing chromium content, the minor phase present changes in composition and structure from Fe_3C to Cr_7C_3 to $Cr_{23}C_6$, and finally the brittle intermetallic compound $FeCr$ occurs (reference 4, p. 78).

The minor-phase types of the steels of molybdenum and of tungsten exhibit marked similarity, as shown in table VII. A study of a high-speed steel containing 17.2 percent tungsten and 0.64 percent carbon showed an iron-tungsten carbide of the M_6C-type, Fe_4W_2C, to be present and similar investigations with molybdenum steels indicated that the analogous carbide, Fe_4Mo_2C, existed (reference 5). Reference 5 indicated that the range of homogeneity of these carbides extends at least over the range of composition between the limits $Fe_4(Mo\ or\ W)_2C$ and $Fe_3(Mo\ or\ W)_3C$. Other investigators (reference 9) have succeeded in isolating from a molybdenum steel a carbide powder whose composition corresponds to that of Fe_3Mo_3C.

Titanium nitride was identified in Nimonic 80 and Inconel W, columbium nitride in 19-9DL, and the nitrides of titanium and columbium in Inconel X. These alloys nominally contain no nitrogen; however, in a steel that presumably contained 2.28 percent titanium, 0.05 percent carbon, and no nitrogen, Hume-Rothery and colleagues (reference 6), using the electrolytic method employed in this investigation, identified titanium nitride in addition to titanium carbide and ferrotitanide, Fe_2Ti. Diffuse interference lines were found in the diffraction pattern between the corresponding lines of the titanium carbide and titanium nitride, from which they inferred that titanium carbide and titanium nitride, both face-centered cubic structures of about the same lattice parameter, formed a continuous series of solid solutions. No such diffuse lines were noticed in the patterns obtained from the residues of Inconel W, an alloy in which both titanium nitride and titanium carbide were identified.

The known carbides of the $M_{23}C_6$ type and their lattice parameters are shown in the following table (data from reference 10):

Isomorph	Lattice parameter, a (A)
$Cr_{23}C_6$	10.638
$(Cr,Fe)_{23}C_6$	10.565
$(Fe,Mo)_{23}C_6$	10.527
$(Cr,Mo)_{23}C_6$	?
$(Cr,W)_{23}C_6$	10.73

This type of carbide has been detected in one binary system, that of chromium with carbon. The occurrence of the carbides of the M_6C type has not been noted in any of the binary systems with carbon. Apparently, an element such as iron, chromium, or cobalt and a heavier element, such as tungsten or molybdenum, must be present for the formation of carbides of the M_6C type. Table VII shows that the percentage of molybdenum and tungsten needed for formation of the carbide type $M_{23}C_6$ is lower than that needed in forming the M_6C type.

DISCUSSION OF RESULTS

As shown in table VI, titanium nitride was observed in the high-nickel alloys, Nimonic 80, Inconel W, and Inconel X. Columbium nitride was also identified in the last alloy. The presence of these nitrides in alloys that presumably contain no nitrogen raises the question of whether nitrogen was present in the nickel or in the titanium as an impurity. The second possibility is more probable when it is noted that Hume-Rothery (reference 6) also detected titanium nitride in a steel containing very little, if any, nickel. The reaction of titanium carbide with nitrogen at temperatures above 1500° C and its resulting decarburization (reference 11) is an indication that titanium has more affinity for nitrogen than for carbon. The crystal structures of titanium nitride, titanium carbide, columbium nitride, and columbium carbide are similar, inasmuch as all possess the face-centered cubic NaCl-type structure with the maximum difference in lattice parameters being in the order of 5 percent. The values of the lattice parameters of the titanium nitride phases listed in table IV show good agreement with that of 4.233 angstrom units for the titanium nitride found in titanium steel (reference 6).

Columbium nitride, CbN, was detected in three alloys: N155, an alloy containing 0.11 percent N and 1 percent Cb; Inconel X, an alloy which has been discussed; and 19-9DL. In order to account for the presence of columbium nitride rather than columium carbide in these alloys, columbium must be postulated to be a stronger nitride- than carbide-former. These experimental results merely confirm that titanium and columbium react similarly with carbon and, quite conceivably therefore, also react similarly with nitrogen, a nonmetal similar to carbon. In line with this reasoning, because titanium is a stronger carbide-former than columbium (reference 4, p. 64), titanium may also be expected to be a stronger nitride-former than columbium. Columbium nitride, however, was identified in 19-9DL and not titanium nitride, even though both titanium and columbium were present in this alloy. Whereas aluminum usually accompanies titanium as a minor alloying element in the high-temperature alloys investigated, the alloy 19-9DL contains no aluminum (table VI). Both aluminum and titanium possess great affinity for oxygen (reference 4, passim), an element which is always present to some extent as an impurity. If the assumptions are made that aluminum is a stronger oxide-former than titanium and that titanium has a greater affinity for oxygen than for nitrogen, the presence of columbium nitride and not of titanium nitride in the alloy 19-9DL, which contains no aluminum, can be explained in the following manner. Where titanium, columbium, and aluminum are present as minor elements in an alloy, the aluminum first combines with the oxygen present leaving titanium free to combine with the nitrogen. If any nitrogen exists after titanium has reacted with it, columbium nitride forms. However, where aluminum is not present, as in the case of 19-9DL and Inconel X, titanium combines with the oxygen present before combining with the nitrogen. If an excess of titanium exists after reacting with the oxygen, titanium nitride forms; if no titanium remains after reacting with the oxygen, the columbium of the alloy reacts with the free nitrogen, forming columbium nitride. The first condition, presumably, is representative of Inconel X and the second condition, of 19-9DL. The greater percentage by weight of titanium in Inconel X than in 19-9DL lends credence to this theory that leads to the conclusions that Inconel X has an excess of titanium over that necessary to combine with the oxygen present in this alloy and that in 19-9DL the excess titanium does not exist.

In all alloys containing titanium or columbium or both, the corresponding carbide was identified wherever the nitride phase was not detected and in some cases in conjunction with the nitride phase. The carbide-forming elements of the alloys examined, listed in order of increasing tendency to form carbides, are

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chromium, molybdenum, tungsten, columbium, and titanium (reference 4, p. 64). By this listing, if only carbides are obtained as minor phases, the presence of titanium carbide and columbium carbide in alloys containing titanium and columbium is to be expected before the carbides of molybdenum, tungsten, and chromium. In the alloys S590 and S816, the percentage of columbium carbide present is large enough to be detected without concentration of the sample (reference 2).

The carbide type $M_{23}C_6$ was identified in seven alloys: 17W, 19-9DL, Vitallium, 61, 6059, 422-19, and X-40. This type of carbide is lower in molybdenum or tungsten content than the M_6C type. Inasmuch as titanium and columbium have greater affinity for carbon than either molybdenum or tungsten, the presence of carbides of molybdenum and tungsten is not to be expected if titanium and columbium are present in an amount more than that required to combine with all the carbon present.

The carbide type M_6C was identified in three alloys: 16-25-6, S590, and Hastelloy B. In 16-25-6 and in Hastelloy B, in which no other carbide was detected, the ratio of molybdenum to carbon content was higher than in the alloys containing the minor phase $M_{23}C_6$. In the alloys containing a high percentage of molybdenum and tungsten relative to the carbon content, the carbide of the higher molybdenum and tungsten content, M_6C, therefore seems to exist.

Chromium carbide, Cr_7C_3, was detected in the two alloys, Inconel and Stellite No. 6. Inconel contains no carbide former other than chromium, and Stellite No. 6 contains a relatively high carbon percentage (1.3 percent) with a resultant low ratio of the molybdenum-plus-tungsten content to the carbon content as compared to the alloys already discussed. Inasmuch as the carbon is therefore not combined with the stronger carbide formers, molybdenum and tungsten, a chromium carbide should be found in both these alloys; the presence of Cr_7C_3 confirms this reasoning. Because Stellite No. 6 has 27 percent chromium and 1.3 percent carbon (table I), a large quantity of the carbide Cr_7C_3 probably exists throughout this alloy and this large amount is probably capable of dissolving the tungsten of the alloy. The relatively low tungsten content in the carbide was indicated by the backgrounds of the diffraction patterns obtained with cobalt and chromium radiation. Cobalt radiation caused the residues consisting mainly of this

phase to fluoresce heavily, whereas excellent patterns were obtained with chromium radiation. If the carbide of the type Cr_7C_3 had contained any considerable quantity of tungsten, heavy fluorescence would have also occurred with chromium radiation.

The presence of the minor phases identified in the various alloys is roughly correlated with the ratio of the content of carbide-forming elements to the carbon content of the alloy in table VIII. Titanium and columbium, the strongest carbide formers, are here assumed to combine with carbon in the ratio of one atom of metal to one atom of carbon. Any carbon that remains after these two elements have combined with it is free to combine with tungsten and molybdenum. The first column lists the ratio of atomic percentage of titanium to the atomic percentage of carbon. The second column lists the ratio of atomic percentage of columbium to the atomic percentage of carbon. If the sum of these two ratios were 1, if perfect distribution and mixing took place, and if only carbides were obtained as minor phases, all the carbon would combine with titanium and columbium, leaving no excess of carbon or of the metallic element. If this sum were more than 1, an excess of metallic element would be present; if less, an excess of carbon would be present that could be distributed to the molybdenum and tungsten atoms of the alloy. The third column is the ratio of the atomic percentage of molybdenum plus tungsten to the atomic percentage of the "free" carbon, that is, the carbon remaining for combination with the molybdenum and tungsten.

Table VIII shows that whenever titanium or columbium is present in an alloy, at least one of the minor phases detected is a nitride or carbide of either element regardless of the percentages of tungsten, molybdenum, or chromium that may exist in the alloy. This observation substantiates the conclusion that both columbium and titanium have great affinity for carbon and nitrogen. When the ratio of the atomic percentage of titanium to the atomic percentage of carbon is 12.5 in the high-nickel alloys, Inconel X, Inconel W, and Nimonic 80, titanium nitride is present. As the sum of the ratios of the first two columns decreases, carbides other than those of titanium or columbium make their appearance. When the ratio of the atomic percentage of columbium to the atomic percentage of carbon is 1.3, faint lines appearing on the patterns obtained from the residue of S590 were identified as those of the carbide of the higher molybdenum and tungsten content, M_6C. This carbide, however, was not identified in S816, an alloy comparable to S590, which indicates that this carbide probably would be absent or would be present in quantities too

small for detection by X-ray diffraction if a more thorough mixing took place. When the sum of the ratios of the first two columns is further decreased to 0.5 and more carbon thereby is released to the molybdenum and tungsten atoms, the carbide of the lower molybdenum and tungsten content, $M_{23}C_6$, is found. When no titanium or columbium exists, the carbide Cr_7C_3 is present in the two alloys Inconel and Stellite No. 6, which contain small percentages relative to the carbon content of molybdenum and tungsten and a chromium content in the order of 20 percent. As the ratio of the atomic percentage of molybdenum and tungsten to the atomic percentage of carbon increases with no titanium or columbium present, the carbide containing the molybdenum and tungsten atoms changes from $M_{23}C_6$ to M_6C. The finding of $M_{23}C_6$ in the alloy 19-9DL when the ratio of atomic percentage of molybdenum and tungsten to the atomic percentage of carbon available for combination is 1.3 (table VIII) as well as the detection of M_6C in the alloy S590 when this ratio is theoretically infinite tends to confirm the conclusion that $M_{23}C_6$ appears when this ratio is low and that M_6C appears when this ratio is high.

Because complex carbides are present in the alloys examined, the alloying elements are not independent of each other. This concept agrees with the findings in reference 12, which states that the strong carbide-forming elements, when simultaneously present in steel, have an interaction that serves to decrease their individual effects on hardenability.

SUMMARY OF RESULTS

An X-ray diffraction investigation of the minor phases of 20 high-temperature alloys resulted in the identification of seven minor phases, columbium carbide, columbium nitride, titanium carbide, titanium nitride, chromium carbide (Cr_7C_3), and carbides of the $M_{23}C_6$ and M_6C types (where M is any metallic atom). Columbium carbide was identified in each alloy containing columbium with the exception of 19-9DL, N155, and Inconel X, in which columbium nitride was found. Titanium carbide was identified in each alloy containing titanium, with the exception of Nimonic 80 and Inconel X, in which titanium nitride was detected, and the further exception of 19-9DL.

In this investigation, the following relations of alloy composition to the formation of minor phases were found:

1. When the ratio of the atomic percentage of titanium to that of carbon is 12.5 in the nickel-base alloys, titanium nitride is found.

2. Columbium and titanium are effective nitride and carbide formers.

3. When titanium is not present in these alloys, in order for columbium alone to combine with all the carbon of an alloy, it must exist in a quantity appreciably above that theoretically required.

4. In the high-temperature alloys containing a quantity of chromium in the order of 20 percent with small percentages, relative to the carbon content, of other stronger carbide-forming elements, the carbide Cr_7C_3 is found.

5. With an increase in the ratio of the atomic percentage of molybdenum and tungsten to the atomic percentage of carbon available to these elements for combination, the carbide containing the molybdenum and tungsten atoms tends to change from $M_{23}C_6$ to M_6C.

Flight Propulsion Research Laboratory,
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TABLE I - TYPICAL COMPOSITIONS OF 20 HIGH-TEMPERATURE ALLOYS

Alloy	Chemical composition (percent)									
	C	Cr	Ni	Co	Mo	W	Cb	Ti	Fe	Other
Cr-Ni-Fe base										
16-25-6	0.15	16	25	--	6	---	---	---	51	N 0.18
17W	.5	13	19	--	1	2.5	---	---	60	
19-9DL	.3	19	9	--	1.2	1.2	0.4	0.3	67	
Discaloy 25	.05	13	25	--	3	---	---	1.8	55	Al .2
Cr-Ni-Co-Fe base										
S590	0.4	20	20	20	4	4	4	---	25	
N155	.3	20	20	20	3	2	1	---	32	N 0.11
K-42-B	.05	18	42	22	---	---	---	2.2	14	Al .2
Refract-aloy 26	.05	18	37	20	3	---	---	2.8	18	Al .2
Cr-Ni base										
Nimonic 80	0.05	21	75	--	---	---	---	2.5	0.7	Al 0.6
Inconel W	.05	14	75	--	---	---	---	2.5	6	Cu .1 Al .6
Inconel X	.05	15	73	--	---	---	1	2.5	7	
Inconel	.05	14	78	--	---	---	---	---	7	Cu .2
Cr-Co base										
Vitallium[a]	0.2	28	2.5	62	5.5	---	---	---	1	
61[a]	.4	28	1	67	---	5	---	---	1	
Stellite No. 6[a]	1.3	27	---	65	---	4	---	---	---	Si 2.7
Cr-Ni-Co base										
6059[a]	0.4	26	33	33	5	---	---	---	1	
422-19[a]	.4	26	15	51	6	---	---	---	1	
X-40[a]	.5	25	10	55	---	7	---	---	.6	
S816	.4	20	20	44	4	4	4	---	3	
Mo-Ni base										
Hastelloy B	0.12	0.27	64	--	29	---	---	---	5	

[a]Cast; all other samples were taken from hot-rolled bars.

TABLE II - X-RAY DIFFRACTION PATTERNS OF UNIDENTIFIED RESIDUES

OBTAINED BY ELECTROLYTIC DIGESTION

OF 20 HIGH-TEMPERATURE ALLOYS

[All reagents per liter of solution; Fe-filtered Co radiation employed for all patterns; d, observed interplanar spacing, A; I, estimated relative intensity of a diffraction line; vs, very strong; s, strong; ms, medium strong; m, medium; mw, medium weak; w, weak; vw, very weak; f, faint; di, diffuse]

d	I	d	I	d	I
Pattern 1; alloy, 16-25-6; reagent, 150 g $HC_2H_3O_2$		1.351	f	2.14	ms
		1.327	f	2.09	m
		1.311	w	1.94	mw
		1.276	vw	1.83	f
5.14	vw	1.261	vw	1.75	vw
4.83	w	1.191	vw	1.72	vw
4.28	f	1.162	vw	1.71	vw
3.68	mw	1.140	vw	1.69	vw
3.31	vw	1.120	vw	1.64	m
3.08	f	1.102	w	1.61	w
2.96	m	1.088	w	1.56	f
2.87	f	1.056	vw	1.51	ms
2.78	vw	.987	f	1.48	m
2.70	s			1.44	mw
2.52	vs	Pattern 2; alloy, 17 W; reagent, 150 g H_2CrO_4		1.376	w
2.41	f			1.306	f
2.21	mw			1.292	w
2.16	vw			1.278	f
2.09	m	7.32	ms	1.237	vw
2.03	f	6.08	vw	1.141	f
1.84	mw	5.20	mw	1.090	vw
1.80	vw	4.16	w	1.071	vw
1.70	m	3.31	s	1.046	f
1.66	f	2.94	mw	1.019	vw
1.64	f	2.68	mw	.984	vw
1.61	m	2.61	w	.975	f
1.52	f	2.52	vs	.967	vw
1.48	ms	2.46	m	.958	vw
1.45	m	2.34	f	.938	f
1.366	f	2.28	m		

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TABLE II - X-RAY DIFFRACTION PATTERNS OF UNIDENTIFIED RESIDUES
OBTAINED BY ELECTROLYTIC DIGESTION
OF 20 HIGH-TEMPERATURE ALLOYS - Continued

950

d	I	d	I	d	I
Pattern 3; alloy, 17W; reagent, 50 g $HC_2H_3O_2$		1.247	f, di	**Pattern 7; alloy, Refractaloy 26; reagent, 150 g NH_4OH**	
		1.149	f, di		
		1.126	f, di		
		1.107	f, di		
4.95	vw	1.088	f, di		
4.16	vs	1.043	f, di	7.24	s
3.35	vw	.946	f, di	5.18	mw
2.95	vw	.938	f, di	4.16	f
2.67	m			3.27	s
2.57	w	**Pattern 5; alloy, N155; reagent, 150 g NH_4OH**		2.60	w
2.50	vw			2.53	s
2.44	s			2.43	vw
2.24	mw			2.28	w
2.18	mw	5.97	vw	1.94	vw
1.91	f	5.35	vw	1.64	mw
1.78	vw	4.31	w	1.51	vw
1.71	ms	4.16	f	1.44	vw
1.59	f	3.69	f	1.375	vw
1.56	m	2.69	s		
1.50	m	2.52	s	**Pattern 8; alloy, Nimonic 80; reagent, 50 g HCl**	
1.45	w	2.46	vw		
1.41	vw	2.26	f		
1.313	vw, di	2.21	vw		
1.258	f	2.08	mw	4.78	s
1.238	f	2.03	vs	4.66	vw
1.120	vw, di	1.98	f	4.35	s
1.040	f	1.92	f	2.95	w
.975	f	1.84	vw	2.86	w
.945	f	1.80	vw	2.71	vw
		1.77	f	2.61	f
Pattern 4; alloy, Discaloy 25; reagent, 150 g HNO_3		1.71	f	2.55	f
		1.69	w	2.48	m
		1.56	f	2.42	vw
		1.51	f	2.36	f
		1.48	vw	2.14	s
4.00	f	1.45	f	2.10	w
3.60	w	1.433	vw	2.06	mw
2.93	vw	1.171	mw	1.96	vw
2.67	s	1.010	f	1.93	w
2.48	vs			1.85	vw
2.16	mw	**Pattern 6; alloy, K-42-B; reagent, 150 g NH_4OH**		1.52	w
1.82	w			1.50	w
1.67	s			1.48	vw
1.52	vw, di			1.294	f
1.47	vw, di	7.63	vs	1.261	vw
1.433	m	2.61	s		
1.299	vw	1.53	m		
		1.314	vw		

TABLE II - X-RAY DIFFRACTION PATTERNS OF UNIDENTIFIED RESIDUES

OBTAINED BY ELECTROLYTIC DIGESTION

OF 20 HIGH-TEMPERATURE ALLOYS - Continued

d	I	d	I	d	I
Pattern 9; alloy, Nimonic 80; reagent, 150 g HNO_3		Pattern 10; alloy, Nimonic 80; reagent, 50 g NaOH		1.280	w
				1.256	w, di
				1.231	vw
				1.189	vw
5.86	vw	2.95	mw	1.172	f
5.27	vw	2.76	w	1.083	vw, di
4.20	w	2.67	vs	1.068	f, di
2.66	ms, di	2.35	w	1.038	vw, di
2.44	f	2.17	vw		
2.37	ms, di	2.01	f	Pattern 12; alloy, 422-19; reagent, 150 g NH_4OH	
2.29	mw, di	1.71	w		
2.06	s, di	1.64	vw		
2.02	w	1.55	s		
1.89	f	1.48	vw, di	4.63	m
1.75	vw	1.339	vw	3.03	f
1.66	vw	1.293	f, di	2.70	vw
1.59	f	1.018	f, di	2.60	f
1.54	mw	.991	f, di	2.35	mw
1.46	m, di			2.24	m
1.374	f	Pattern 11; alloy, Vitallium; reagent, 150 g HNO_3		2.16	m
1.283	vw			2.11	w
1.249	w, di			2.03	vs
1.197	vw			1.91	s
1.160	f	2.62	vw, di	1.76	s
1.135	f	2.36	vw, di	1.56	vw
1.097	f	2.14	vs	1.48	w
1.070	f	2.08	m, di	1.374	vw
1.063	f	2.03	mw, di	1.246	ms, di
1.053	f	1.98	vw	1.172	vw, di
1.036	f	1.93	w, di	1.145	vw, di
.954	vw, di	1.84	f	1.081	f, di
.929	vw, di	1.80	m, di	1.062	ms, di
.912	f	1.71	vw	1.045	vw, di
				1.016	w, di

950

TABLE II - X-RAY DIFFRACTION PATTERNS OF UNIDENTIFIED RESIDUES

OBTAINED BY ELECTROLYTIC DIGESTION

OF 20 HIGH-TEMPERATURE ALLOYS - Concluded

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d	I	d	I	d	I
Pattern 13; alloy, X-40; reagent, 50 g $HC_2H_3O_2$		1.62	f	Pattern 15; alloy, Hastelloy B; reagent, 150 g $H_3PO_4 \cdot H_2SO_4$	
		1.56	f		
		1.50	vw		
		1.44	vw		
6.75	m	1.39	f		
6.00	vw	1.285	f	7.45	s
5.40	s	1.256	vw	6.32	mw
4.91	f	1.169	f	5.27	m
4.44	s	1.135	f	4.20	vw
4.12	f	1.085	f	3.66	w
3.74	vw	1.067	f	3.32	vs
3.57	w	1.052	f	3.11	f
3.38	ms	1.042	f	2.94	w
3.24	ms			2.67	m
3.18	ms	Pattern 14; alloy, Hastelloy B; reagent, 50 g $HC_2H_3O_2$		2.54	ms
2.94	ms			2.50	ms
2.88	vw			2.46	vw
2.74	f			2.35	vw
2.55	m			2.29	m
2.48	vw	7.41	ms	2.19	w.
2.41	mw	5.27	mw	2.06	ms
2.34	mw	4.63	vw	1.94	w
2.25	m	3.32	vs	1.83	vw
2.16	mw	2.66	m, di	1.79	w
2.05	m	2.54	s	1.76	f
1.95	w	2.28	ms	1.74	f
1.93	f	1.95	vw	1.68	vw
1.88	w	1.75	f	1.64	w
1.85	vw	1.64	m	1.59	vw
1.79	w	1.55	w, di	1.51	vw
1.74	vw	1.44	vw	1.47	w
1.71	vw	1.38	f	1.44	w
1.66	vw			1.37	vw
				1.303	f
				1.267	vw
				1.200	f
				1.095	f
				1.081	vw

TABLE III - X-RAY DIFFRACTION PATTERNS OF SEVEN MINOR PHASES PRESENT IN HIGH-TEMPERATURE ALLOYS

[Fe-filtered Co radiation employed for all of patterns except for Cr_7C_3 (V-filtered Cr radiation); M, any metallic atom of alloy being considered; d, observed interplanar spacing, Å; I, estimated relative intensity of diffraction line; vs, very strong; s, strong; ms, medium strong; m, medium; mw, medium weak; w, weak; vw, very weak]

d	I	d	I	d	I	d	I	d	I	d	I	d	I
CbO (in S590)		CbN (in N155)		TiC (in K-42-B)		TiN (in Inconel W)		Cr_7C_3 (in Inconel)		$M_{23}C_6$ type (in 17W)		M_6O type (in Hastelloy B)	
2.54	vs	2.52	vs	2.47	s	2.41	m	2.27	ms	2.37	s	2.69	m
2.21	s	2.18	s	2.14	vs	2.09	vs	2.09	s	2.16	s	2.47	m
1.56	ms	1.55	ms	1.51	m	1.48	s	2.06	w	2.03	vs	2.20	s
1.333	ms	1.322	ms	1.294	mw	1.264	m	2.03	vs	1.87	m	2.08	vs
1.277	mw	1.267	mw	1.238	w	1.212	m	1.83	mw	1.79	mw	1.91	m
1.106	w	1.098	w	1.073	vw	1.051	w	1.80	m	1.76	w	1.80	w
1.016	m	1.008	m	.985	vw	.967	m	1.77	w	1.68	w	1.52	w
.991	m	.983	m	.963	vw	.944	s	1.74	m	1.62	vw	1.410	mw
.906	ms	.898	m					1.60	vw	1.60	mw	1.324	mw
								1.44	w	1.48	vw	1.303	w
								1.338	mw	1.414	w	1.277	ms
								1.260	vw	1.326	w	1.251	mw
								1.211	w	1.285	mw	1.091	m
								1.202	vs	1.249	ms	1.064	mw
								1.182	vs	1.225	m	1.050	mw
								1.170	vs	1.163	w	.978	vw
								1.167	vs	1.065	mw	.961	vw
										1.035	vw	.950	mw
										.984	w	.932	ms
										.968	w	.906	ms
										.956	vw		
										.926	mw		
										.908	w		

TABLE IV - LATTICE PARAMETERS OF MINOR PHASES FOUND IN

20 HIGH-TEMPERATURE ALLOYS

[M, any metallic atom of alloy being considered]

Alloy	Lattice parameters (A)							
	a	a	a	a	a	c	a	a
	CbC	CbN	TiC	TiN	Cr_7C_3		$M_{23}C_6$	M_6C
16-25-6 17W 19-9DL Discaloy 25		4.396	4.310				10.60 10.63	10.97
S590 N155 K-42-B Refractaloy 26	4.435	4.401	4.305 4.306					10.98
Nimonic 80 Inconel W Inconel X Inconel		4.402	4.323	4.229 4.233 4.229	13.99	4.523		
Vitallium 61 Stellite No. 6					14.03	4.524	10.65 10.64	
6059 422-19 X-40 S816	4.436						10.65 10.65 10.62	
Hastelloy B								10.87
Limits of accuracy	±0.008	±0.008	±0.008	±0.008	±0.03	±0.008	±0.02	±0.02

TABLE V - RESIDUES OBTAINED BY ELECTROLYTIC

IN TWELVE REAGENTS OF

[M, any metallic atom of

Reagent										
Electrolyte	Concentration (g/liter)	16-25-6	17W	19-9DL	Discaloy 25	S590	N155	K-42-B	Refractaloy 26	Nimonic 80
HCl	50	M_6C	$M_{23}C_6$	$M_{23}C_6$	TiC	CbC+M_6C	CbN	TiC	Alloy	[a]Pat. 8
	150	M_6C	$M_{23}C_6$	$M_{23}C_6$+CbN	TiC	CbC	CbN	TiC	TiC	TiN
HNO_3	50	Alloy	[a]Pat. 14	Alloy	Alloy	CbC	CbN	[a]Pat. 1	Alloy	TiN
	150	Alloy	[a]Pat. 14	CbN	[a]Pat. 4	CbC	CbN	Alloy	Alloy	[a]Pat. 9
H_2SO_4	50	Alloy	Alloy	Alloy	[a]Pat. 4	CbC	CbN	Alloy	Alloy	Alloy
	150	Alloy	$M_{23}C_6$	CbN	[a]Pat. 4	CbC	CbN	Alloy	TiC	TiN
H_3PO_4	50	Alloy	Alloy	Alloy	[a]Pat. 4	CbC	CbN	[a]Pat. 1 and 14	Alloy	TiN
	150	Alloy	[a]Pat. 14	Alloy	[a]Pat. 4	CbC	CbN	[a]Pat. 1	Alloy	TiN
H_2CrO_4	50	Alloy	Alloy	[a]Pat. 1	[a]Pat. 4	CbC+M_6C	CbN	[a]Pat. 1	Alloy	Alloy
	150	Alloy	[a]Pat. 2	[a]Pat. 1	Alloy	CbC	CbN	Alloy	Alloy	TiN
$H_2C_2O_4$	50	Alloy	Oxalate	Oxalate	Oxalate	CbC+Oxalate	CbN+Oxalate	Oxalate	Oxalate	Oxalate
	100	Oxalate	Oxalate	Oxalate	Oxalate	CbC+Oxalate	Oxalate	Oxalate	Oxalate	Oxalate
$HC_2H_3O_2$	50	Alloy	[a]Pat. 3	[a]Pat. 1	[a]Pat. 1	CbC	CbN+[a]Pat. 1	Alloy	Alloy	Alloy
	150	[a]Pat. 1	[a]Pat. 1	[a]Pat. 1	[a]Pat. 1	CbC	CbN+[a]Pat. 1	[a]Pat. 1	[a]Pat. 1	TiN
$HNO_3 \cdot HCl$	50	Alloy	Alloy	$M_{23}C_6$+CbN	Alloy	CbC	CbN	Alloy	Alloy	Alloy
	150	M_6C+[a]Pat. 14	Alloy	Diffuse pat.	Alloy	CbC	CbN	Alloy	Alloy	TiN
$FeCl_3 \cdot HCl$	50	M_6C	Alloy	Alloy	[a]Pat. 1	CbC+M_6C	Alloy	Alloy	TiC	[a]Pat. 8
	150	M_6C	Alloy	$M_{23}C_6$+CbN	TiC+[a]Pat. 1	CbC	CbN	TiC	TiC	TiN
$H_3PO_4 \cdot H_2SO_4$	50	Alloy	Alloy	Alloy	Alloy	CbC	Alloy	[a]Pat. 1	Alloy	Alloy
	150	M_6C	$M_{23}C_6$	CbN	[a]Pat. 4	CbC	CbN	Alloy	Alloy	TiN
NaOH	50	Alloy	Alloy	Diffuse pat.	Alloy	CbC	CbN	Alloy	Alloy	[a]Pat. 10
	150	Diffuse pat.	Diffuse pat.	Diffuse pat.	[a]Pat. 1	CbC	Diffuse pat.	Alloy	Alloy	Alloy
NH_4OH	50	Alloy	Alloy	Diffuse pat.	[a]Pat. 1	CbC	Alloy	Alloy	[a]Pat. 1	TiN
	150	Alloy	Alloy	Diffuse pat.	[a]Pat. 1	CbC	[a]Pat. 5	[a]Pat. 6	[a]Pat. 7	Alloy

[a]See table II.

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DIGESTION OF 20 HIGH-TEMPERATURE ALLOYS

TWO CONCENTRATIONS EACH

alloy being considered]

Residue

Alloy

Inconel W	Inconel X	Inconel	Vitallium	61	Stellite No. 6	6059	422-19	X-40	S816	Hastelloy B
TiN+TiC	TiN+CbN	Cr_7C_3	$M_{23}C_6$	$M_{23}C_6$	Cr_7C_3	$M_{23}C_6$	$M_{23}C_6$	$M_{23}C_6$	CbC	M_6C
TiN+TiC	TiN+CbN	Cr_7C_3	$M_{23}C_6$	$M_{23}C_6$	Cr_7C_3	$M_{23}C_6$	$M_{23}C_6$	$M_{23}C_6$	CbC	M_6C
Alloy	Alloy	Alloy	$M_{23}C_6$	$M_{23}C_6$	Alloy	Alloy	Alloy	$M_{23}C_6$	CbC	Alloy
Alloy	Alloy	Alloy	[a]Pat. 11	Alloy	Alloy	$M_{23}C_6$	$M_{23}C_6$	$M_{23}C_6$	CbC	Alloy
Alloy	Alloy	Cr_7C_3	$M_{23}C_6$	$M_{23}C_6$	Cr_7C_3	$M_{23}C_6$	$M_{23}C_6$	$M_{23}C_6$	CbC	Alloy
Alloy	Alloy	Cr_7C_3	[a]Pat. 11	Alloy	Alloy	Alloy	$M_{23}C_6$	$M_{23}C_6$	CbC	Alloy
Alloy	Alloy	Cr_7C_3	$M_{23}C_6$	Alloy	Alloy	$M_{23}C_6$	$M_{23}C_6$	$M_{23}C_6$	CbC	Alloy
Alloy	Alloy	Cr_7C_3	$M_{23}C_6$+ [a]Pat. 11	$M_{23}C_6$	Cr_7C_3	$M_{23}C_6$	$M_{23}C_6$	$M_{23}C_6$	CbC	Alloy
Alloy	Alloy	Cr_7C_3	Alloy	$M_{23}C_6$	Cr_7C_3	Alloy	$M_{23}C_6$	$M_{23}C_6$	CbC	[a]Pat. 14
Alloy	TiN	Alloy	Alloy	$M_{23}C_6$	Alloy	$M_{23}C_6$	$M_{23}C_6$	$M_{23}C_6$	CbC	[a]Pat. 14
Oxalate	Oxalate	Oxalate	Oxalate	$M_{23}C_6$+ Oxalate	Alloy	Oxalate	$M_{23}C_6$+ Oxalate	$M_{23}C_6$+ Oxalate	CbC+ Oxalate	Oxalate
Oxalate	Oxalate	Oxalate	Oxalate	Oxalate	Oxalate	Oxalate	Oxalate	$M_{23}C_6$+ Oxalate	CbC+ Oxalate	Oxalate
Alloy	Alloy	Alloy	Alloy	Alloy	Cr_7C_3	$M_{23}C_6$	$M_{23}C_6$	[a]Pat. 13	CbC	[a]Pat. 14
TiN	Alloy	Alloy	$M_{23}C_6$	$M_{23}C_6$	Cr_7C_3	$M_{23}C_6$	$M_{23}C_6$	Alloy	CbC	Alloy
TiN	Alloy	Cr_7C_3	$M_{23}C_6$	$M_{23}C_6$	Diffuse pat.	$M_{23}C_6$	Alloy	$M_{23}C_6$	CbC	Alloy
TiN	Alloy	Alloy	$M_{23}C_6$	$M_{23}C_6$	Diffuse pat.	$M_{23}C_6$	$M_{23}C_6$	$M_{23}C_6$	CbC	Diffuse pat.
TiN+TiC	TiN	Cr_7C_3	$M_{23}C_6$	$M_{23}C_6$	Cr_7C_3	$M_{23}C_6$	$M_{23}C_6$	Alloy	CbC	Alloy
TiN	TiN+CbN	Cr_7C_3	$M_{23}C_6$	$M_{23}C_6$	Cr_7C_3	$M_{23}C_6$	$M_{23}C_6$	$M_{23}C_6$	CbC	M_6C
Alloy	Alloy	Cr_7C_3	$M_{23}C_6$	$M_{23}C_6$	Cr_7C_3	$M_{23}C_6$	Alloy	$M_{23}C_6$	CbC	Alloy
Alloy	Alloy	Cr_7C_3	[a]Pat. 14	$M_{23}C_6$	Cr_7C_3	$M_{23}C_6$	$M_{23}C_6$	$M_{23}C_6$	CbC	[a]Pat. 15
Alloy	Alloy	Diffuse pat.	Alloy	Alloy	Alloy	$M_{23}C_6$	Alloy	Alloy	CbC	[a]Pat. 11
Alloy	Diffuse pat.	Diffuse pat.	Alloy	$M_{23}C_6$	Cr_7C_3	Alloy	$M_{23}C_6$	$M_{23}C_6$	CbC	Diffuse pat.
Alloy	Alloy	Cr_7C_3	$M_{23}C_6$	$M_{23}C_6$	Cr_7C_3	$M_{23}C_6$	Alloy	Diffuse pat.	CbC	Diffuse pat.
Alloy	Alloy	Alloy	Alloy	$M_{23}C_6$	Cr_7C_3	$M_{23}C_6$	[a]Pat. 12	Diffuse pat.	CbC	Diffuse pat.

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TABLE VI - MINOR PHASES IDENTIFIED IN 20 HIGH-TEMPERATURE ALLOYS

[M, any metallic atom]

Alloy	Principal elements	Minor elements	Minor phases
16-25-6 17W 19-9DL Discaloy 25	Cr, Ni, Fe	Mo, N, C Mo, W, C Mo, W, Cb, Ti, C Mo, Ti, Al, C	M_6C $M_{23}C_6$ CbN, $M_{23}C_6$ TiC
S590 N155 K-42-B Refractaloy 26	Cr, Ni, Co, Fe	Mo, W, Cb, C Mo, W, Cb, N, C Ti, Al, C Mo, Ti, Al, C	CbC, M_6C CbN TiC TiC
Nimonic 80 Inconel W Inconel X Inconel	Cr, Ni	Ti, Al, Fe, C Ti, Al, Fe, Cu, C Ti, Cb, Fe, C Cu, Fe, C	TiN TiN, TiC TiN, CbN Cr_7C_3
Vitallium 61 Stellite No. 6	Cr, Co	Mo, Fe, C W, Fe, Ni, C W, Si, C	$M_{23}C_6$ $M_{23}C_6$ Cr_7C_3
6059 422-19 X-40 S816	Cr, Ni, Co	Mo, Fe, C Mo, Fe, C W, Fe, C Mo, W, Cb, Fe, C	$M_{23}C_6$ $M_{23}C_6$ $M_{23}C_6$ CbC
Hastelloy B	Mo, Ni	Cr, Fe, C	M_6C

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TABLE VII – MINOR PHASES OBSERVED IN FOUR TYPES OF STEEL

[Data from references 5 (pp. 78-81) to 8]

	Cr steel	Mo steel	W steel	Ti steel
Increas- ing con- tent of alloying element	Fe_3C $^a Cr_7C_3$ $^a Cr_{23}C_6$ FeCr	Fe_3C $^a(Fe,Mo)_{23}C_6$ $^a(Fe,Mo)_6C$ Mo_2C Fe_7Mo_6	Fe_3C $^a(Fe,W)_{23}C_6$ $^a(Fe,W)_6C$ WC Fe_7W_6	Fe_3C $^a TiN$, TiN-TiC, $^a TiC$ Fe_2Ti

^{a}Minor phases found in high-temperature alloys examined.

TABLE VIII - COMPARISON OF CONTENT OF CARBIDE-FORMING ELEMENTS

WITH MINOR PHASES IDENTIFIED

[M, any metallic atom of alloy being considered]

Alloy	Number of Ti atoms per C atom[1]	Number of Cb atoms per C atom[2]	Number of (W+Mo) atoms per C atom available to W and Mo[3]	Minor phase iden-tified
Inconel X	12.5	2.6	------------	TiN, CbN
Refractaloy 26	14.0	------------	∞	TiC
Inconel W	12.5	------------	------------	TiN, TiC
Nimonic 80	12.5	------------	------------	TiN
K-42-B	11.0	------------	------------	TiC
Discaloy 25	9.0	------------	∞	TiC
S816	------------	1.3	∞	CbC
S590	------------	1.3	∞	CbC, M_6C
19-9DL	.3	.2	1.3	CbN, $M_{23}C_6$
N155	------------	.4	3.0	CbN
Inconel	------------	------------	------------	Cr_7C_3
Stellite No. 6	------------	------------	.2	Cr_7C_3
17W	------------	------------	.6	$M_{23}C_6$
61	------------	------------	.8	$M_{23}C_6$
X-40	------------	------------	.9	$M_{23}C_6$
6059	------------	------------	1.5	$M_{23}C_6$
422-19	------------	------------	1.9	$M_{23}C_6$
Vitallium	------------	------------	3.4	$M_{23}C_6$
16-25-6	------------	------------	5.0	M_6C
Hastelloy B	------------	------------	30.3	M_6C

[1] $\dfrac{\text{Atomic percentage of Ti}}{\text{Atomic percentage of C}}$

[2] $\dfrac{\text{Atomic percentage of Cb}}{\text{Atomic percentage of C}}$

[3] $\dfrac{\text{Atomic percentage of (Mo+W)}}{\text{Atomic percentage of C - atomic percentage of (Ti+Cb)}}$